Multispectral Thermal Infrared Sensors

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Abstract

Well calibrated, high resolution multiband thermal infrared (TIR) images of the Earth's surface can provide accurate distributions of surface spectral emittance and temperatures. The multispectral TIR data can be analyzed to provide spatial information about surface properties that cannot easily be obtained in any other way. They can also be used to monitor Earth surface characteristics and rates of change on local to global scales.

Over the last several years, instruments have been flown to image the Earth's surface in a few thermal infrared bands at spectral resolution of about a kilometer or more. The sensors currently collecting data include. the AVHRR and ATSR. The AVHRR has five channels with 1 km spatial resolution; ATSR has four channels with the same resolution. The utility of these instruments over land is somewhat reduced because of the high spatial variability of land surfaces and the non uniform spectral emissivity of the land surface materials. These factors combine to make an accurate determination of land temperatures difficult.

In the next few years we can anticipate new instruments which will have several to many bands in this spectral region with much higher spatial resolution. These new instruments will allow much more accurate determination of surface spectral emissivity and surface temperature. One of the first of this new generation of thermal infrared imaging instruments will be ASTER. Other projected instruments include the MTI, PRISM, IRSUTE and Sacagawea.

Future instruments will require significant advances in technology in the areas of detectors and coolers and in the areas of spacecraft systems and operations.

The next decade should prove to be an exciting one in the thermal infrared remote sensing arena. We anticipate that the advent of the sensors discussed here will develop a demand for high spatial resolution multispectral, thermal infrared data.

Introduction

Over the last several years, instruments have been flown to image the Earth's surface in a few thermal infrared bands at a spectral resolution of about a kilometer or more. These include such instruments as AVHRR and ATSR. While these instruments have proved extremely useful for measurement of sea surface temperature, their utility over land is somewhat reduced because of the high spatial variability of land surfaces and the non-uniform spectral emissivity of the land surface materials. These factors combine to make an accurate determination of land temperatures difficult. However, in the next few years we can anticipate new instruments which will have several to many bands in this spectral region with much higher spatial resolution. These new instruments will allow much more accurate determination of surface spectral emissivity and surface temperature. One of the first of this new generation of thermal infrared imaging instruments will be ASTER. It is being built by MITI in Japan and is scheduled to fly on the NASA EOS-AM1 platform in 1998. Other projected instruments include the MTI, PRISM, IRSUTE and Sacagawea. We will briefly describe the scientific rationale for flying imaging infrared instruments, describe the current instruments, and then discuss in more detail the next generation of instruments which are in the construction or planning stages.

Science Rationale

Well calibrated, high spectral and spatial r [illegible] (TIR) images of the Earth's surface can provide. accu [illegible] emittance and surface temperatures. Even if one is only [illegible] temperature, high spectral resolution is desirable to enable separation of, spectral effects in the measured radiance, and to remove the atmospheric effects. Removal of atmospheric effects can also be aided by multiple view angles and/or use of global assimilation models of the current state of the atmosphere.

“he multispectral TIR data are a function of the composition and character of surface materials and the surface heating cycle, and can be analyzed to provide spatial information about surface properties that cannot easily be obtained in any other way. They can also be used to monitor Earth surface characteristics and rates of change at local to global scales. Some of the subject areas include:

compositional mapping
heat and moisture fluxes
climatological processes
evapotranspiration
changes in soil moisture
hydrology
biomass distributions
vegetation monitoring
vegetation stress
lithology
renewable and nonrenewable resource distribution
land use/land cover

The region of the thermal infrared that is most useful for these studies is from 8-13 µm, because of the coincidence of an atmospheric window, measurable differences in emissivities of key materials such as silicates, and the existence of a sensitive detector material. ‘I’he region from 3 to 5 µm, a second atmospheric window, adds to the identification of other materials including the nitrates, sulfates and senescent vegetation. A combination of data from both spectral regions allows one to better determine and remove the effects of the atmosphere on the signal received by the sensor.

Current Sensors

AVHRR

The Advanced Very High Resolution Radiometer (AVHRR) is a visible-through-thermal infrared imaging radiometer that has been providing daily coverage of the Earth in four or five spectral bands at a nominal resolution of 1 km since 1978 (AVHRR was preceded by a series of continuously improved instruments since the first high-resolution thermal infrared imaging instrument developed by JPL was flown on “1’11<0S in 1965). The primary mission of AVHRR is to provide daytime and nighttime sea surface temperatures and information on ice, snow, and cloud formations. (Malila and Anderson, 1986). The AVHRR that flew on the NOAA/TIROS N meteorological series satellite was a four channel instrument with wavelengths shown in Table 1.

Table 1. Four-channel AVHRR

Channel 1	0.55 -0.9 pm
Channel 2	0.725 -1.1 µm
Channel 3	10.5 -11.5 µm
Channel 4	3.s5 - 3.93 µm

The AVHRR instruments that have flown onboard NOAA-7, -9 and -11 since June, 1981 have had five channels (see Table 2). The additional infrared channel provides better cloud discrimination and is useful for determining sea surface temperature. With careful atmospheric correction, the AVHRR temperature resolution of the sea surface is 0.6°C. Horizontal temperature gradients of 0.2°C can he resolved.

Table 2. Five-channel [illegible]

Channel 1	0.58 -0.68 μm
Channel 2	0.725 -1.1 μm
Channel 3	10.5 -11.3 μm
Channel 4	3.55-3.93 μm
Channel 5	11.5- 12.5 μm

The AVHRR instrument's 110.8° cross-track scan equates to a swath of 2700 km. The orbital period is about 102 minutes and there are 14.1 orbits per day.

Because the 1 km resolution data are too voluminous to be captured daily, the data are subsampled and averaged onboard and then transmitted to central receiving stations as Global Area Coverage (GAC) data with a nominal resolution of 4 km providing full global coverage. The 1 km resolution Local Area Coverage (LAC) data may be acquired on request, Thus far, the AVHRR has produced data from over 70,000 orbits. The Pathfinder AVHRR data are archived and distributed by the EOSDIS Distributed Active Archive Center at Goddard Space Flight Center (Goddard DAAC).

ATSR

ESA successfully launched the ATSR-1 (Along Track Scanning Radiometer) onboard ERS-1 in July 1991. Its four infrared channels, with 1 km spatial resolution, are scanned by an off-axis conical scanning mechanism enabling the Earth's surface to be viewed at two angles, nadir and forward (0° and 52°) in two curved swaths 500 km wide and separated along the same orbit by about 700 km along track. Data from the two swaths are combined to eliminate the atmospheric influence in the calculation of the primary ATSR product: Sea Surface Temperature (SST). ESA launched the second ERS in April 1995, which contained as part of its payload an enhanced version of the ATSR. ATSR-2 has, in addition to the infrared bands, three VNIR bands which are experimental in nature and designed with potential land applications in mind. Presently both ATSR instruments are fully functioning and producing data. The third instrument of the series, AATSR will fly onboard Envisat, which is due to be launched at the end of 1998. AATSR is essentially a copy of ATSR-2.

The primary mission of ATSR is to provide a long time series of global SSTs at the 50 km scale to an accuracy of better than 0.5K. In addition to the primary product, high resolution SST, cloud products, radiation products and, with ATSR-2, vegetation products are being produced.

The ERS and Envisat platforms will fly on a near polar orbit at an altitude of 780 km. The repeat cycle is on a 3 day or 35 day repeat, with an equator nodal crossing time of approximately 10:00 am.

Each ATSR has an IFOV at nadir of 1 km, and a FOV of 500 km, and acquires data globally both day and night.

Table 3 shows the spectral and radiometric characteristics of ATSR.

Table 3. ATSR

Wavelength (micron)	Bandwidth FWHM (micron)	Tmin (K)	Tmax (K)	NEΔT@270K (K)	Lmin W/m2/sr/micron	Lmax	SNR @ rho=0.5%
0.550	0.020				0.0	500	20:1
0.660	0.020				0.0	450	20:1
0.870	0.020				0.0	300	20:1
1.600	0.060				0.0	70	20:1
3.7	0.4	0	311	0.08			
11.0	0.9	200	321	0.05			
12.0	1.0	200	318	0.05			

All performances are at instrument level. The VNIR bands are not available for ATSR-1.

Future Sensors

ASTER

The Advanced Spaceborne Thermal Emission and Reflection Radiometer (ASTER) is a facility instrument selected for launch in 1998 on the first NASA Earth Observing System spacecraft, EOS-AM1 (Yamaguchi, et al., 1994). The ASTER instrument is being sponsored and built in Japan, with funding provided by the Japanese Ministry of International Trade and Industry (MITI). The Japan Resources Observation Systems Organization (JAROS) is responsible for the design and development of ASTER which is subcontracted by JAROS to NEC, MELCO, Fujitsu and Hitachi.

The objectives for the ASTER instrument are to obtain high spatial resolution multispectral targeted data in the visible and infrared wavelength regions. An international team of scientists are developing the algorithms and software that will be used to process the data from the instrument into standard and special data products. The standard data products will be produced at the Earth Resources Observation System (EROS) Data Center (EDC) Land Processes Distributed Active Archive Center (LPDAAC) at Sioux Falls, South Dakota. Special data products will be produced by the Science Team members at their home institutions.

The ASTER Standard Data Products that will be ready at launch will include radiance at the sensor, brightness temperature at the sensor, atmospherically-corrected surface-leaving radiance, surface emissivity, surface kinetic temperatures, decorrelation stretch images and local Digital Elevation Models (DEMs). In addition, other standard data products may be developed postlaunch, and several special data products will be produced by the ASTER investigators at their home institutions. These data products can be used by the general science community in studies of surface radiation balance, evaporation and evapotranspiration, vegetation, soils, the hydrogeologic cycle, surface-atmosphere fluxes, surface change detection, glacial studies, volcanic processes, sea ice and clouds.

ASTER is comprised of three radiometers: (1) a three-channel visible-near infrared two-telescope radiometer (VNIR) that is capable of providing stereo data for the production of digital elevation models, (2) a six-channel shortwave infrared radiometer (SWIR), and (3) a five-channel thermal infrared radiometer (TIR). All three radiometers can be operated independently and all three are individually pointable. The instrument features high spatial and radiometric resolution. The nadir-viewing swath width is 60 km. With its pointing capability, ASTER is capable of viewing any point on Earth every 16 days. Because of its polar orbit, it can view any point above 45° every 7-9 days and any point above 69°, every 3-4 days. It takes 48 days to provide full surface coverage.

The ASTER characteristics are given in Table 4.

Table 4. ASTER

Radiometer	Spectral range	Data rate	Radiometric resolution	Spatial resolution
VNIR	Nadir bands 0.52-0.60 μ 0.63-0.69 μ 0.76-0.86 μ Stereoscopic bands 0.76-0.86 μ	62 Mbps	<0.5%	15111
SWIR	6 bands 1.6-1.7 μ 2.145-2.185 μ 2.185-2.225 μ 2.235-2.2$5 μ 2.295-2.365 μ 2.360-2.430 μ	23 Mbps	<0.5%-1.3%	30 m
TIR	5 bands 8.125-8.475 μ 8.475-8.825μ 8.925-9.275 μ 10.25-10.95 μ 10,95-11.65 μ	4.1 Mbps	<3K	90 m

Thermal dissipation, power use and data volume all limit the number and extent of observations. The VNIR and SWIR telescope systems will be capable of up to an average duty cycle of 8%, e.g., they can be operated continuously for up to 16 minutes in one orbit. The TIR will be capable of a 16% duty cycle. The instrument data rates are 62 Mbps for the VNIR, and 23 and 4.1 Mbps for the SWIR and TIR respectively, The two orbit average data rate allowance is 8.3 Mbps.

The Science Team has proposed a basic operating plan for ASTER which allocates 5% of it's viewing time for emergency observations (natural disasters, volcanic eruptions, forest fires, floods, etc., 20% for EOS scientist-requested targets for specific research topics, 50% for regional multi-temporal monitoring (regional change), and 25% for global mapping, e.g. to observe the entire land surface, cloud-free, at least once during the 5-year mission.

The Moderate Resolution imaging Spectroradiometer (MODIS) will be flown on EOS-AM1 with the ASTER instrument and also on the EOS-PM satellite (Asrar and Dokken, 1993). The MODIS mission will provide Earth coverage in 36 spectral bands from 0.4 to 14 μm with a spatial resolution of 250 to 1000 meters. Principal MODIS standard data products include cloud mask and cloud properties, aerosol concentration and optical properties, vegetation and land cover, snow and sea ice cover, surface reflectance and surface temperature with 1 km resolution, ocean color, and concentration of chlorophyll-a and chlorophyll fluorescence.

Since ASTER is the only high-spatial resolution imager planned for EOS-AM 1, it will be relied upon to provide surface temperatures, surface emitted and reflected radiances, and digital elevation models at a finer spatial scale than the other EOS instruments and can **provide detailed measurements at the** process or field measurement level of qualities which MODIS can monitor daily on a global basis.

Multispectral Thermal Imager (MTI)

The Multispectral Thermal Imager (MTI) is an instrument with its own dedicated spacecraft sponsored by the Department of Energy (DOE). The purpose of this one-of-a-kind research and development mission is to demonstrate and evaluate multispectral and thermal imaging technology for military and civilian applications.

The mission is being conducted for DOE by Sandia National Laboratory (SNL), Los Alamos National Laboratory (LANL) and the Savannah River Technology Center. Participants include Air Force Phillips Laboratory, Ball Aerospace. System Division (S/C), Hughes Danbury Optical Systems, Hughes Santa Barbara Research Center, and other government and university entities.

The instrument and spacecraft have just completed the preliminary design process, and launch is expected somewhere between mid- 1997 and mid-1998. The funded mission life is 14 months, although the design life is three years. A launch vehicle has not yet been defined. MTI has a 36-inch aperture, and 15 channels operated in a push broom mode, using line arrays and interference filters in all channels. The spatial resolution from the 545 km sun-synchronous (1 pm equator crossing time), orbit is 5 m in the short wavelength channels and 40 m in the long wavelength channels. The cross track swath width is 12 km and the orbit repeat cycle is 7 days. Duty cycle is expected to be about six scenes per day. The channel locations are specified in Table 5.

Table S. MTI Characteristics

Channel	Wavelength (micrometers)	Spectral resolution	Channel	Wavelength (micrometers)	Spectral resolution
A	0.45--0.52	5 In	1	1.55-–1.75	5 m
B	0.52- 0.60	5 m	J	3.5--- 4.1	40 m
C	0.62---0.68	5 m	K	4.87---5.07	40 m
D	0.76--0.86	5 m	L	8.() ---8.4	40 In
E	0.86-0.90	5 m	M	8.4 -- 8.8s	4(I m
F	0.91--4).97	5 m	N	10.15 ---11.5	40 m
G	0.99---1.04	5 m	O	2.09----2.35	40 m
H	1.36---1.39	5 m			

MTI is intended to be self-contained with respect to atmospheric correction, in all channels. Each near-nadir scene acquisition is to be accompanied by a second scene of the same area with an emission angle in the range 45° to 60°. The atmospheric correction is derived from knowledge of the local atmosphere (a la ATSR). LANL is responsible for this work. The end-to-end goal is to keep the error under 10 for the kinetic temperature of water. There is no similar goal over land although there is an interest in using the multispectral data (including the thermal) to identify material properties.

PRISM

For the **post-2000** era, ESA has defined an Earth Observation strategy which consists of two series of platforms: the Earth Watch, and Earth Explorer missions.

The Earth Watch series will create an operational capability while the Earth Explorers will be a series of research and semi-operational instruments. One candidate mission in the Earth Explorer line is PRISM (Processes Research by an Imaging Space Mission). It is currently in the pre-phase A stage of development under the auspices of the EOPP (Earth Observation Preparatory Programme at ESA-ESTEC). It consists of an imaging spectrometer and TIR radiometer covering the 400 nm to 12 μm range at a spatial resolution of 50 m.

The primary mission of PRISM will be the study of land surface processes: the energy, water and biogeochemical fluxes (Rast and Keal y, 1993). B y sensing at high spectral and spatial resolution, PRISM will enable a deeper understanding of the processes that occur at the local scale. ‘his knowledge can then be extrapolated through time and in space using process models and lower resolution remote sensing instruments to derive regionally and then globally significant results. The synergistic use of PRISM is foreseen with sensors such as MERIS, MODIS, the AVHRR and ATSR series of instruments and the Meteosat second generation series (Mark land, 1991).

The imaging spectrometer component will be used to determine biogeochemical parameters for soil and mineralogical studies. The TIR component is required to determine the thermal fluxes required in combined energy, water and biogeochemical models. These will form the basis of nested models leading to integration into regional and global scale circulation models.

The focus of the TIR instrument design is on the recovery of land surface temperature (LST). The derivation of emissivity information is considered of secondary importance as the VNIR/SWIR component of PRISM will provide a wealth of information on the geology and pedology of the test sites. The LST in conjunction with the other capabilities of PRISM will provide inputs to the following areas of scientific interest: energy and radiation balance, hydrology, vegetation studies, micrometeorology, microclimate research and desertification.

The orbit will be near-polar, sun-synchronous, yaw-steered, with an equator crossing time of around 11:00 am. The orbit, in conjunction with the across-track pointing capability will ensure a revisit time of three days at low latitudes. The higher revisit time at European latitudes is in keeping with the experimental nature of the instrument. The PRISM mission is not intended to map the entire 1 Earth surface with the PRISM mission, but rather to study in detail a number of well chosen sites as often as possible.

The imaging spectrometer component spans the 0.4 μm to 2.35 μm spectral range in 0.01 μm wide contiguous spectral bands.

The thermal component is detailed in Table 6.

Table 6. PRISM Characteristics

Wavelength (micron)	Bandwidth FWHM (micron)	Tmin (K)	Tmax (K)	NEΔT@300K (K)
3.8	0.6	231	361	0.1
3.8	0.6	361	855	25@855K
8.8	1.4	212	345	0.1
10.8	1.0	203	360	0.1
11.8	1.0	204	356	0.1

This table shows the requirements for Black Body Temperatures (1111”1’) at the entrance of the instrument. The 3.8 µm band is able to sense high temperatures in order to measure forest fire and volcanic events.

The interface requirements to the plat form specify a power consumption of less than 500W, a mass of less than 400 kg with onboard storage capacity of 100 Gbit which will be downloaded at high latitude ground stations for processing and distribution. This storage capacity should give a maximum duty cycle of approximately 5% per orbit.

An image will be 50x 50 km on ground for which the IFOV is 50 m. An across-track pointing capability of ±30 at intervals of 1° will ensure the ability to minimize the revisit time to chosen sites of interest. The. spatial resolution of 50 m has been determined from an ESA study of spatial resolution for typical scales in the European landscape.

The number, position and bandwidth of each band is presently the subject of preparatory studies within EOPP. The results of these studies will in all probability lead to a refinement of the above configuration, and the identification of a 1ST retrieval algorithm. With the guidance of ESA's Science Advisory Group on land surface processes the mission requirements and performance parameters will become defined in detail. In keeping with ESA's continuing commitment to environmental remote sensing and its Earth Observation strategy, the Agency intends to develop a high spatial and spectral mission dedicated to the support of land surface studies.

IRSUTE

IRSUTE (Infrared Satellite Unit for Terrestrial Environment) is an instrument being considered by CNES for launch in the year 2003 or later (Durpaire, et al., 1995).

The general objectives of IRSUTE are to demonstrate the potential applications of high spatial resolution thermal infrared data for operational environmental monitoring. The major objective is surface parameter retrieval at the field scale. The main parameters to be inferred from IRSUTE data are net radiation, emissivity and temperature, aerodynamic temperature, and mass and energy fluxes combining IRSUTE data with other available satellite data (SAR, Meteosat, AVHRR, ATSR, Spot/Vegetation).

Other applications to be studied are in the areas of vegetation monitoring, soil characterization and environment, including biomass determination and crop yield estimate at the field scale, average fluxes for mesoscale weather prediction, and evapotranspiration for budget estimation at the watershed scale.

Experiments with the airborne Thermal Infrared Multispectral Scanner (TIMS) have demonstrated the potential for high resolution thermal IR spectral data to identify minerals and map the geological soil composition. Soil parameters such as composition and water storage capacity could be obtained in winter conditions (bare soil).

For the environment, potential applications of IRSUTE data are identification of area touched by night frosts, thermal pollution detection, urban heat island identification, determination of areas for water culture, and small-scale ocean stream studies.

The planned IRSUTE channels are given in Table 7.

Table 7.

Spectral channels	NEAT for T=290K	Wavelength FWHM
IR1	0.1 K	3.5-4.0
IR2	0.1K	8.2-8.7
IR3	0.1K	8.7-9.2
IR4	0.1K	9.8-10.8

Temperature dynamic scale: $253 < T(K) < 340$

Visible radiometric requirements include a pixel size of 50 m with two options possible: one panchromatic channel λ_c -0.6 pm, or two chromatic channels λ_c -0.65 and 0.85 μm with $NE\Delta\rho < 0.15\%$.

The calibration accuracy between IR channels will be 0.1 K and between visible channels, 3%. The absolute calibration accuracy for the IR channels will be 1 K and for the visible channels, 10%.

IRSUTE geometrical requirements include 40 to 60 m pixel size, 10 to 50 km swath width, ±35° across track viewing, 45° along track viewing, and 0.3 pixel multispectral registration.

System constraints include sun synchronous orbit, orbit altitude between 450 and 800 km, repetitivity of observations between one to four days maximum, onboard recording capability, and S-band for image data transmission.

Sacagawea

A team at the Jet Propulsion Laboratory is studying Sacagawea as a potential Lewis and Clark type mission --- that is, a "faster, better, cheaper" technology demonstration instrument and satellite. Performance goals for Sacagawea include a spatial resolution of 15 to 30 m, 5-10 spectral channels in each of the 3-5 μm and 8 to 13 μm wavelength regions, an NEAT of= 0.1 K at 300K and onboard calibration. At the same time, the instrument must be significantly smaller than current instruments.

One of the major technological problems with thermal infrared imagers is that in order to achieve the desired spectral and spatial resolution with sufficient signal-to-noise, the optics must be large. Such an instrument will also require significant advances in technology in the areas of detectors and coolers. Technology areas that are being investigated include quantum well infrared photodetectors (QWIP's), adsorption coolers and large lightweight optics systems. Also, in the area of space craft systems and operations, the following are being studied: autonomous planning, scheduling and operations, agile spacecraft maneuvers, automatic cloud avoidance, high precision pointing and high-rate downlink.

Summary

The next decade should prove to be an exciting one in the thermal infrared remote sensing arena. Just as Landsat developed a large user community in the 1970s when multispectral VNIR data became available over users' areas of interest, we anticipate that the advent of the sensors discussed here will develop a demand for high-spatial-resolution multi-spectral, thermal infrared data. It is important that the technology be developed to allow continued improvement in these types of instruments.

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